High Q Resonating Cantilevers for *In Situ* Measurements of Ferromagnetic Films

John Moreland and Ted J. Hubbard
National Institute of Standards and Technology,
325 Broadway, Boulder CO

***Abstract*- We describe cantilevers developed for in-situ measurements of submonolayer ferromagnetic films. The cantilevers are optimized for use in a resonating torque micro balance magnetometer that measures the magnetic moment of thin films as they are being deposited onto the cantilever. Dynamic feedback is used to balance the magnetic torque by applying a mechanical force at the base of the cantilever that is just equal but opposite to the magnetic torque. The dynamic feedback minimizes mass loading and temperature dependent elastic modulus effects that change the resonant frequency of the cantilever during deposition.**

I. INTRODUCTION

In this paper we describe the design, fabrication, and test procedures for micromachined cantilevers developed for the purpose of sensing the magnetic moment of submonolayer ferromagnetic thin films. Typically, magnetic film properties are determined *ex situ* with induction-field (*B-H*) loopers that measure the $M_r t$ product for the film, where M_r and t are the saturation magnetization and the thickness of the film, respectively. However, it is desirable to measure the magnetic moment of a thin-film *in situ* during its deposition. Here we describe a method based on a micromechanical sensor that can be located in a deposition system much the same way as conventional quartz crystal thickness monitors.

II. PRINCIPLE OF OPERATION

The torque on a uniformly magnetized thin film with a strong in-plane anisotropy is $T_M = \mu_0 \, |\boldsymbol{m} \times \boldsymbol{H_T}| = \mu_0 m H_T$, assuming a 90º angle between H_T and the magnetic moment m of the film. For the paddle configuration described in Fig. 1 we assume that the torque on the film acts as a bending moment concentrated at the end of the cantilever spring neglecting any bending of the cantilever substrate. The displacement z is therefore [1]

$$z = \frac{6T_M l_c^2}{E w_c t_c^3} = \frac{6\mu_0 m H_T l_c^2}{E w_c t_c^3} = \frac{6\mu_0 M_s t_f a_f H_T l_c^2}{E w_c t_c^3}, \tag{1}$$

with the parameters defined in Table 1 (note that the magnetic torque is defined to be $T_M = \mu_0 M_s a_f t_f H_T$). At the cantilever resonance there is a Q enhancement of $z_r = Q \times z$.
In principle, the fundamental noise source for these measurements is the Brownian motion of the cantilever, which can be expressed as an equivalent thermal noise per root hertz of [2]

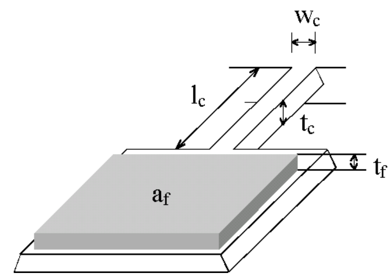

Fig. 1. Micromachined silicon paddle cantilever. The magnetic film is deposited on the substrate only.

$$z_{\min} = \sqrt{\frac{2k_B T}{\pi k_s Q f_o}} \tag{2}$$

where k_s is the spring constant: $k_s = E w_c t_c^3 / 6 l_c^2$, Q is the mechanical quality factor, f_o is the resonant frequency: $f_o = \sqrt{k_s / m_c}$, and $k_B T$ is the thermal energy. The signal-to-noise ratio per root hertz is then

$$SNR = \frac{T_M}{k_s} \sqrt{\frac{\pi k_s Q f_o}{2k_B T}} = T_M \sqrt{\frac{\pi Q f_o}{2 k_s k_B T}} \quad . \tag{3}$$

For the cantilevers studied (3) predicts a *SNR* of 10-20,000. Increasing the area of the magnetic film on the cantilever substrate increases sensitivity to magnetic moment changes of the film per unit of thickness. However, as the area of the paddle increases so does its mass and thus the resonant frequency of the cantilevers decreases. *SNR* can be optimized by increasing Q and f_o or decreasing k_s. Increasing f_o is problematic since either k_s must be increased sacrificing *SNR* or m_c must be decreased by reducing the area of the paddle. Therefore, in this paper we focus on decreasing k_s and increasing Q to optimize cantilever performance.

TABLE 1

EXPERIMENTAL PARAMETERS

Symbol	Definition	Value
μ_0	permeability of free space	$4\pi \times 10^{-7}$ H/m
M_s	saturation magnetization	1×10^{6} A/m (Ref.1)
a_f	magnetic film area	1 mm^2
H_T	torque field	0 - 700 A/m rms
l_c	cantilever length	1200 µm
w_c	cantilever width	25 - 200 µm
t_c	cantilever thickness	19 - 27 µm
E	Young's Modulus	1.79×10^{11} N/m^2
Q	cantilever quality factor	50,000 – 200,000

For f_o below 1 kHz, electronic noise begins to dominate the measurement. Cantilevers with dimensions shown in Table 2 have a reasonable f_o for this application. These designs have the additional advantage of larger cantilevers that are easily handled for testing. In principle, thinner cantilevers with smaller paddles would have an equivalent *SNR* but we found that significant curling occurs when films are deposited on 3 μm thick cantilevers due to the residual stress of the magnetic films.

III. Resonating Torque Microbalance Instrument

The cantilevers are mounted in a resonating torque microbalance instrument shown schematically in Fig. 2. An optic-fiber interferometer is used to measure the deflection of the cantilever [3]. A small coil close to the cantilever provides the ac torque field H_T of up to 700 A/m rms at the resonant frequency of the cantilever. H_T is perpendicular to the film and generates a torque due to in-plane shape anisotropy. An oscillator supplies the reference signal for a lock-in amplifier as well as current to the coil through a power amplifier. The cantilever deflection signal from the interferometer is phase shifted and amplified, and then applied to the cantilever piezoelectric mount. The phase and magnitude of the piezo signal are adjusted to balance the magnetic torque on the cantilever. This process, referred to as *force feedback* [4], alleviates resonant-frequency stability problems associated with temperature drift and mass loading effects. A lock-in amplifier measures the piezo feedback signal that is proportional to the magnetic moment of the magnetic film. The cantilever is placed between a pair of SmCo permanent magnets that provide a static bias field H_0 of 10 kA/m. Under these conditions, the film should be fully saturated in plane.

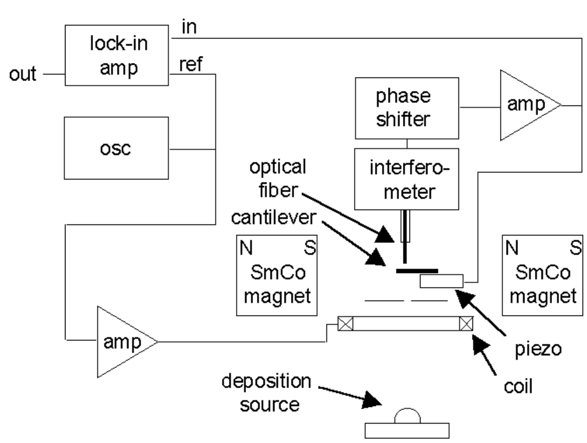

Fig. 2. Schematic diagram showing the components of a resonating torque microbalance magnetometer (not to scale).

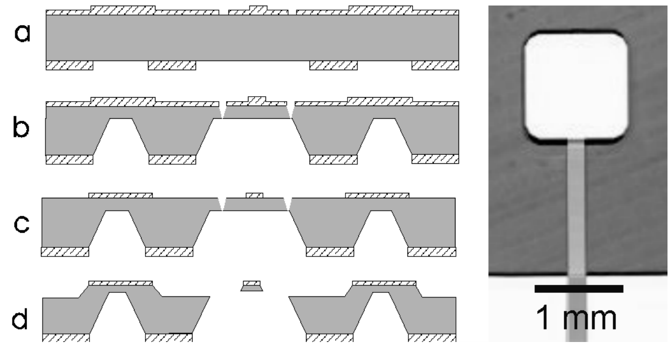

Fig. 3. Fabrication processing steps for paddle cantilever (right). Photomicrograph of paddle cantilever (left).

IV. Cantilever Fabrication

We use a bulk silicon micromachining process [5] for fabricating cantilevers (see Fig. 3). Beginning with 75 mm diameter double sided wafers we deposit 500 nm of low stress LPCVD nitride. The front side and backside of the wafer are patterned (with backside alignment) for etching with a RIE. All of the nitride is removed on the backside whereas only 250 nm is removed on the front side. A second pattern is transferred to the front side of the wafer and subsequently etched in the RIE to define vias that will form etch pits that serve as depth gauges during the wet etch (Fig. 3a) The wafer is then transferred to a 20% (by weight) KOH bath at 80°C and etched until light appears through pinholes formed at the apex of the depth gauge etch pits (Fig. 3b). The wafer is then removed from the KOH bath, rinsed in methanol, and transferred to the RIE etcher where 250 nm of nitride is removed from the front side (Fig. 3c). The wafer is then transferred back to the KOH bath and etched until the cantilevers are released (Fig. 3d). After release the wafers are rinsed with methanol and etched in 48% HF until all of the remaining nitride is removed. A finished cantilever is shown in Fig. 3. We fabricate the cantilever in a frame that is connected to the wafer by break-off tabs, eliminating the need for a wafer-dicing step.

V. Cantilever Operation

A. *Q Measurements: Open Loop*

Measurements of the free decay of the beam are done in vacuum. We observed that for pressures below 10^{-3} Pa viscous damping affects are eliminated. The beam is first excited by the piezo with a continuous sine wave f_o and the rms amplitude of vibration is detected by a lock-in as described in Fig. 2. The sine wave is then gated on and off over a long time period (100-200 seconds) to allow sufficient time and cycles for signal to ramp up and ring down. Note that we require $f_{gate} < f_o/Q$ (e.g. if f_o = 1 kHz and Q = 200,000, $f_{gate} <$ 0.05 Hz and there must be at least 200 seconds per gate). As shown in Fig. 4, when the sine wave is gated off, the amplitude decays exponentially. When the sine wave is gated on, the output overshoots and decays to an equilibrium value. Note that the transient response beats with a period of several seconds before it decays due to the fact that the excitation frequency is not exactly equal to f_o. We fit the free ring-down period with an exponential to determine Q according to the formula

$$z_{rms} \propto e^{-pf_o t / Q} \tag{4}$$

The time constants for beams of widths 25, 50, 100, 150, and 200 μm were measured at pressures of 2-3 × 10^{-4} Pa. The time constants were between 10 and 40 seconds and Q ranged between 50,000 and 200,000 as shown in Table 2. The Q's measured with magnetic excitation of the cantilever were the same as those measured for piezo excitation.

B. Q Measurements: Closed Loop

Dynamic feedback is used to balance the magnetic torque by applying a mechanical force at the base of the cantilever that is just equal but opposite to the magnetic torque. Spurious results are observed for open loop detection: the dynamic feedback approach minimizes mass loading and temperature dependent elastic modulus effects that change the resonant frequency of the cantilever during deposition. In addition, the closed-loop cantilever response time is greatly reduced. When feedback is used the effective Q is reduced without sacrificing SNR [4]. The higher the gain the lower the effective Q. If $\boldsymbol{c}(f)$ is the open loop frequency response, then the closed loop response for a feedback system with constant gain is

$$\hat{\boldsymbol{c}}(f) = \frac{\boldsymbol{c}(f)}{1 - \boldsymbol{hc}(f)} \tag{5}$$

where $\boldsymbol{h}$ is the instrumental feedback gain and

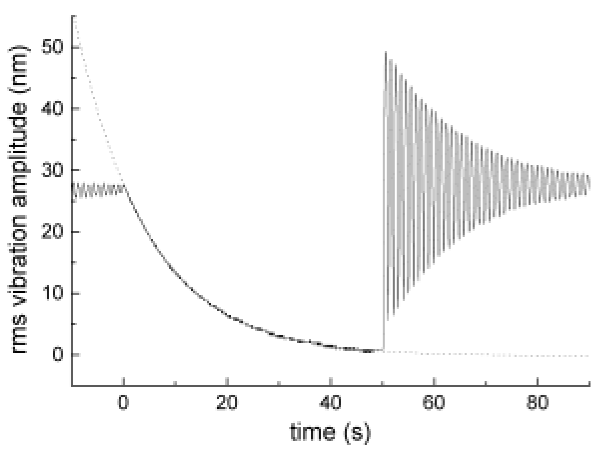

Fig. 4. Time decay data for a 150 um beam.

TABLE 2

OPEN-LOOP Q MEASUREMENTS

#	w_c (μm)	t_c (μm)	l_c (μm)	f_o (kHz)	$\boldsymbol{t}$ (s)	Q (x 1000)
1	25	27	1200	1.406	10.5	46 ± 4
2	50	23	1200	1.588	42.3	211 ± 10
3	100	19	1200	1.897	19.3	115 ± 13
4	150	19	1200	2.125	15.4	102 ± 6
5	200	23	1200	2.409	16.9	128 ± 3

$$\boldsymbol{c}(f) = \frac{f_o^2}{f^2 - f_o^2 - iff_o / Q} \tag{6}$$

is the typical damped harmonic oscillator cantilever response function. In the closed-loop system

$$\hat{\boldsymbol{c}}(f) = \frac{f_o^2}{f^2 - f_o^2 - iff_o / \hat{Q}} \tag{7}$$

where $\hat{Q}$ is the equivalent closed-loop Q, and $\hat{Q} \approx 1/\boldsymbol{h}$.

Fig. 5 shows the resonance curves for the cantilever as a function of feedback gain. The gains used in the closed loop system were on the order of 50 to 100. As expected we observe that $\hat{Q}$ is inversely proportional to η.

The feedback signal is plotted as a function of torque field for a 30 nm thick NiFe film deposited onto the paddle. The response of the instrument is linear as expected over the range shown indicating that torque energy is well below the anisotropy energy of the film. The corresponding noise level for a torque field of 500 A/m was determined to be 0.1% of total signal. We thus derive a magnetic moment thickness sensitivity level of order 0.03 nm $/\sqrt{Hz}$ (see inset in Fig. 6).

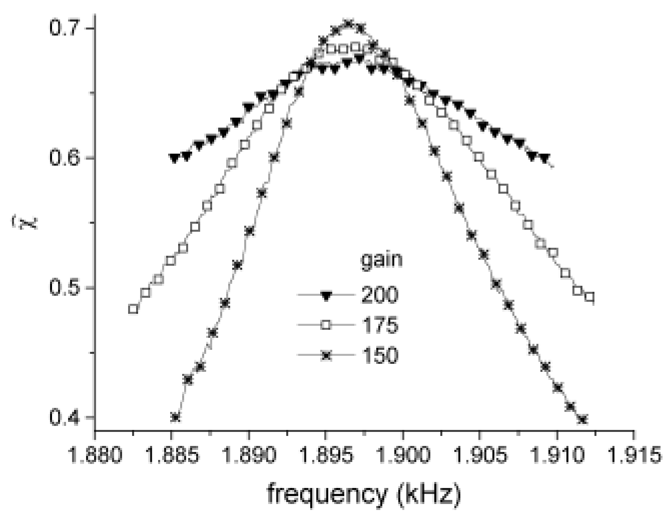

Fig. 5. Cantilever response with feedback loop closed.

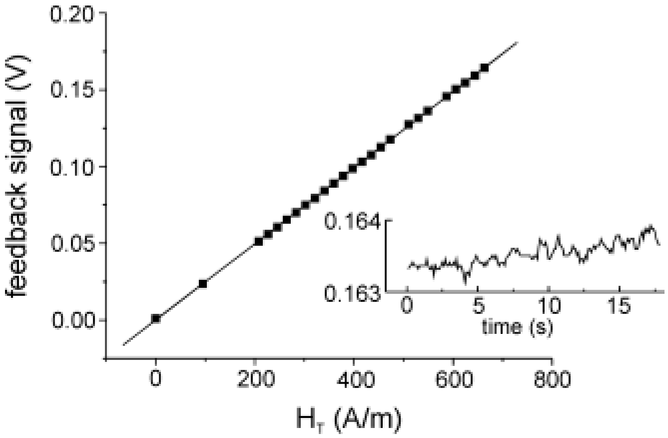

Fig. 6. Feedback signal as a function of torque field for a 30 nm thick NiFe Film. The inset shows the noise level.

VI. Thin Film Deposition Measurements

Fe films (99.9%) were deposited onto custom fabricated single-crystal silicon cantilevers. Depositions were done in a diffusion-pumped vacuum chamber with a liquid nitrogen cold trap. The cantilever was masked by a Si chip with a 1 mm hole positioned 0.5 mm from the cantilever surface. The hole exposes only the cantilever substrate to the deposition source. The cleaved end of the optical fiber was positioned a few micrometers from the back of the substrate near the center. The background pressure during deposition was 2.66×10^{-4} Pa. The films were evaporated from alumina coated tungsten boats at a deposition rate ranging from 0.1 to 1 nm/s. Film thickness was measured with a commercial quartz-crystal thickness monitor with a precision of 0.1 nm.

Fig. 7 shows results for a Fe film deposition. Notice that the moment of the film is nearly proportional to the thickness of the film over the course of the deposition. The deposition rate was varied over time from 0.7 nm/s to 0.5 nm/s and then backs to 0.7 nm/s. Lower deposition rates had lower magnetic moment versus thickness slopes. Lower deposition rates may lead to more water being included in the film and thus decreasing the bulk moment of the film. The average magnetic moment noise level corresponds to 0.2 nm Fe film thickness equivalent.

Similar data can be obtained without active feedback. In such cases the magnetic moment signal is dominated by small shifts in the cantilever resonance frequency caused by thermal and mass loading effects as discussed above. These spurious effects are amplified when operating near the resonance of the cantilever. To check that the active feedback mechanism is working properly, and that the mechanical torque supplied by the piezo is reacting to only the magnetic torque, we deposited a Cu film onto the Fe film (see Fig.7). As expected, the magnetometer shows little response during the Cu deposition. However, during deposition, a 60 Hz 20 A current was flowing through the evaporation boat.

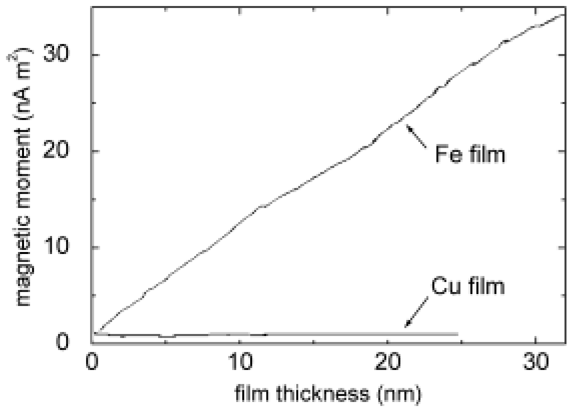

Fig. 7. Magnetic moment measured with the resonating torque microbalance versus thickness versus time during a Fe and a Cu deposition

Apparently, the higher harmonics couple to the cantilever either by electromagnetic or vibrational coupling mechanisms at a level ten times greater than the Brownian noise contribution. The noise level during deposition corresponds to a magnetic-film-thickness sensitivity of 0.2 nm $/\sqrt{Hz}$.

VII. Future Work

The next stage of this project will be to integrate the optic fiber interferometer into a MEMS chip holder thus eliminating the need for a precision translation stage for positioning the fiber relative to the cantilever. The modulation coil and piezo will also be integrated into the chip holder. In addition, we plan to optimize the feedback electronics to further improve *SNR*.

Acknowledgment

The authors thank D. Porpora and Q. Ji who participated in NIST student programs for their help on this project.

References

[1] R. J. Roark, W. C. Young, *Formulas for Stress and Strain*, 5th Edition McGraw-Hill, 1975, p. 105.

[2] D. Sarid, *Scanning Force Microscopy with Applications to Electric, Magnetic, and Atomic Forces* ,Oxford, New York,1991, pp.19-38.

[3] D. Rugar, H.-J. Mamin, and P. Guethner, "Improved fiber-optic interferometer for atomic force microscopy," Appl. Phys. Lett. Vol. 55, pp. 2588-90, 1989.

[4] J. Mertz, O. Marti, and J. Mlynek, "Regulation of a microcantilever response for force feedback," Appl. Phys. Lett. Vol. 62, pp. 2344-2346, 1993.

[5] T. Bayer, J. Greshchner, G. Kraus, H. Weisss, and O. Walter, "Method for Producing Micromechanical Sensors," U. S. Patent 5,051,379, September 24, 1991.